Field Crops Research 222 (2018) 197–208

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Late spring frost impacts on future grapevine distribution in Europe

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ARTICLE INFO

Keywords:
Extreme events
Climate change
Viticulture
Grapevine phenology
Statistical downscaling

ABSTRACT

Viticulture is a worldwide agricultural sector with a relevant economic importance, especially in regions where the climate and environmental conditions meet requirements for the production of high quality wines. The impact of climate change combined with the increased frequency of extreme events predicted for the next future has already shown its potential detrimental effects on viticulture suitability, but few studies currently explored the effect of long-term climate change and extreme events by considering the inter-varietal variability of grapevine. In this study, the combined effect of mean climate change and extreme events (frost events at budbreak and suboptimal temperatures for fruit-set) under future scenarios (RCP 4.5 and 8.5 for two time slices 2036–2065 and 2066–2095, respectively) was evaluated considering four grapevine varieties with very early, early, middle-early and late phenological cycles. The UniChill model calibrated for these varieties was applied in Europe to assess phenological dynamics (budbreak and flowering) using the outputs of a statistical downscaling procedure. Frost impact around budbreak stage as well as the impact of suboptimal temperature around flowering was estimated under present and future scenarios. The results showed a general earlier occurrence of budbreak and flowering stages with a particular relevance on northeastern Europe. The effect of warmer temperatures had a greater effect on late compared to very early and early varieties in western regions. The frequency of frost events at budbreak ($T_{min} < 0$ °C) showed wide variability across Europe, with a strong decrease in western regions (e.g. Spain and UK) and an increase in central Europe (e.g. Germany) for future scenarios. The decrease in the frequency of frost events was especially evident for very early and early varieties. The impact of suboptimal temperatures at flowering evidenced a significant variability across a latitudinal gradient while this effect did not show significant results when comparing cultivars and scenarios. The results of these studies highlighted that in a warmer climate frost events rather than stress at flowering will reshape the distribution of grapevine varieties in Europe.

1. Introduction

Viticulture is a worldwide agricultural sector with a relevant economic importance and a long history of development and evolution (Johnson, 1985; Terral et al., 2010). The most famous wine-producing regions are located in narrow geographical areas with optimal combinations of environmental and human factors, which are described by the *Terroir* concept (Seguin, 1988, 1986; Van Leeuwen et al., 2004). The long history of viticulture adaptation that identifies a specific *Terroir* contributes to characterizing the profile and features of its high-quality wines. However, the high specificity of these climatic niches exposes grapevine growth to the effects of climate change.

More specifically, mean seasonal climate change, inter-annual variability and the increase in frequency and magnitude of extreme weather is expected to strongly affect viticulture in the main wine-producing regions. The impact of mean climate change on the current viticultural regions has already been shown by several authors (Duchêne and Schneider, 2005; Jones et al., 2005; Santos et al., 2012, 2011). Some authors highlighted that warmer temperatures will determine an earlier occurrence of grapevine phenology with a consequent negative impact on grape yield and quality (Fraga et al., 2016; Hannah et al., 2013; Jones et al., 2005; Moriondo et al., 2013; White et al., 2006). These changes will therefore also have detrimental effects on the suitability of the most famous wine-producing regions, determining a shift from current suitable areas towards new ones in the future (Hannah et al., 2013; Moriondo et al., 2013). According to Fraga et al. (2016), viticulture is predicted to reach 55°N by 2070 with a consequent potential increase of wine-producing areas. Although the combined effect of mean climate and variability has long been indicated as detrimental for grape yield and quality (White et al., 2006), climate

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https://doi.org/10.1016/j.fcr.2017.11.018
Received 28 June 2017; Received in revised form 15 November 2017; Accepted 19 November 2017
Available online 06 December 2017

change impact assessments performed so far on grapevine according to different approaches did not consider these possible impacts (Ferrise et al., 2016; Fraga et al., 2016; Hannah et al., 2013; Moriondo et al., 2013).

Moreover, the combined effect of mean climate change and extreme events (i.e. days with $T_{max} >$ 30–35 °C, or days with $T_{min} <$ 0 °C) have a greater impact compared to just the long-term climate change (Ramos et al., 2008; White et al., 2006). In this case, the reduction of suitable areas for high-quality wine production is expected to exceed 50% (White et al., 2006). In particular, the frequency of frost impacts has increased over the last years in different regions (i.e. France, Brun and Cellier, 1992; Canada, Quamme et al., 2010; England, Mosedale et al., 2015; Romania, Bucur and Babes, 2015). However, future warmer temperatures are expected to to move in advance late frost events more than budbreak, leading to a reduction of frost damage in some wine-producing areas (Molitor et al., 2014; White et al., 2006).

On these bases, studies are currently investigating the detrimental effects (i.e. high crop yield variability, decrease in suitable crop areas, etc.) of changing climate conditions on the most valuable crops such as wheat or grapevine (Giannakopoulos et al., 2009; Moriondo et al., 2010; Olesen and Bindi, 2002; Tomasi et al., 2011). A frequently adopted approach is to apply macro-scale analysis for a spatially-explicit assessment of changes affecting grapevine growing suitability at regional, national or continental level (Hannah et al., 2013; Moriondo et al., 2013). Area suitability for growing grapevines is generally evaluated with climatic indices based on a limited number of variables, e.g. heat accumulation and day length during the growing season (Huglin, 1978; Winkler et al., 1974; Zapata et al., 2017). In this context, Jones et al. (2010) showed a spatial analysis on climate variability across wine-producing regions in NW United States using four climatic indices (Huglin Index, Winkler Index, biologically effective degree-day index and average growing season temperatures), which are combined for improving the description of climate and suitability of the regions. Tonietto and Carbonneau (2004) used three complementary indices (Huglin Index, Dryness Index and the Cool Night Index) for a multi-criteria climate classification of the most important wine-producing regions. Other studies, such as White et al. (2006), suggest that the use of these indices should be combined with others able to capture the extreme events effect. In this context, the study of Gabaldón-Leal et al. (2017) showed the impact of mean climate change and extreme events around olive tree flowering.

Building on these premises, the aim of this study is to estimate the dynamics of budbreak and flowering of varieties characterized by very early (VE), early (E), middle-early (ME) and late (L) phenological cycles (Fila, 2012) according to the mean variability of the climate and the unpredictable and severe effect of extreme events. The study includes: (i) the use of a chilling-forcing model for evaluating the impact of climate change on grapevine phenology at European scale; (ii) the assessment of extreme events effect through the estimation of phenological stages (budbreak and flowering).

2. Materials and methods

2.1. Climate datasets

The impact of climate change and future climate variability was evaluated considering Representative Concentration Pathways (RCP; 4.5 and 8.5) proposed by the fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5, IPCC) (IPCC, 2014). The daily outputs of the Aire Limitée Adaptation dynamique Développement InterNational (ALADIN) Regional Climate Model (RCM) (https://www.medcordex.eu/; Ruti et al., 2016) spaced 44 × 44 km, were statistically applied over an observed gridded weather (OBS) dataset covering Europe (MARS project; http://mars.jrc.ec.europa.eu) using Long Ashton Research Station-Weather Generator LARSWG; Semenov and Barrow, 1997) at a spatial resolution of 50 × 50 km.

According to the proposed procedure, OBS observed daily weather data such as minimum and maximum temperature and rainfall (T_{min}, T_{max} and R) for the period 1980–2010 were firstly used to calibrate LARS-WG.

After calibration, 300 years of synthetic daily weather were generated for each grid point at a spatial resolution of 50 km (n° grids = 1732) in Europe to represent the baseline (Present period; Pr).

The daily outputs of ALADIN RCM were used to derive climatic factors to perturb the present baseline. These were expressed as monthly average differences of T_{max} and T_{min} and relative change in rainfall between the relevant RCM baseline (1980–2010) and two different time slices for RCP 4.5 and RCP 8.5, namely: RCP 4.5 2036–2065 (Low CO_2 emission scenario 2036–2065; L1), RCP 4.5 2066–2095 (Low CO_2 emission scenario 2066–2095; L2), RCP 8.5 2036–2065 (High CO_2 emission scenario 2036–2065; H1) and RCP 8.5 2066–2095 (High CO_2 emission scenario 2066–2095; H2). These differences were computed for each RCM grid point covering the European domain.

The relative change in standard deviation of T_{max} and T_{min} and duration of wet and dry spells of R were also calculated. These gridded delta changes were applied over the relevant grids of OBS dataset to perturb the climatology of the baseline. Given the mismatch between the spatial resolution of OBS and RCM, a nearest neighbor approach was used to overlap the different grids finally generating stochastically 300 years of daily data for each 50 × 50 km grid point.

The weather variables obtained for present and future climatic conditions were then used as input of the phenological model for evaluating the responses of changing climate at European NUTS2 region scale (http://ec.europa.eu/eurostat/web/nuts/overview).

2.2. Phenology model

'UniChill' is a Chilling-Forcing (CF) model proposed by Chuine (2000) used for evaluating the grapevine response to different climate change conditions. In relation to the traditional forcing models, which accumulate heat units starting from a fixed date under the assumption that chilling requirement has already been met, (Chuine et al., 1999; Hunter and Lechowicz, 1992), CF model estimates the endo-dormancy duration (the period in which budbreak is inhibited by endogenous factors). Using this kind of model appears more appropriate for future scenario analysis, as winters are predicted to become milder and shorter (Schultz, 2000; Tate, 2001), with a very likely influence on dormancy (García de Cortázar-Atauri et al., 2009).

The length of the endo-dormancy period is calculated by accumulating chilling units from the 1st of September until a critical sum (*Crit*) is reached, which quantifies the specific chilling requirement of the genotype. Starting from this moment, forcing units are accumulated until the specific forcing requirement is met, which initiates budbreak (eco-dormancy refers to the period during which dormancy of the buds is caused by environmental conditions). Flowering date is calculated in a similar manner: starting from the previous stage the forcing units are accumulated until another critical sum is reached. In this context, the simulation is considered failed if flowering is not reached before the 31st of December of the year following the beginning of chilling accumulation.

Table 1 shows the equations to calculate chilling (Eq. (1)) and forcing units (Eq. (2)). Budbreak stage is described by both equations while flowering stage is described only by Eq. (2).

2.3. Grapevine varieties

The phenological traits of four grapevine varieties (*Vitis vinifera L.*) were considered for evaluating the effect of mean climate change and extreme events, by means of the UniChill model.

The budbreak and flowering parameters proposed by Fila (2012) for a VE (Glera), E (Chardonnay), ME (Merlot) and L variety (Cabernet Sauvignon) were applied on all grid points in Europe. The varieties

Table 1
Equations of UniChill model for chilling and forcing accumulation (Chuine, 2000).

UniChill model	
$ChillingUnit = \sum \frac{1}{1 + e^{a_c \cdot (T_{avg} - c_c)^2 + b_c \cdot (T_{avg} - c_c)}}$	(1)
$ForcingUnit = \sum \frac{1}{1 + e^{b_f \cdot (T_{avg} - c_f)}}$	(2)

a_c,b_c,c_c,b_f,c_f parameters for the curve shape; T_{avg} is the daily average temperature (°C); *ChillingUnit* represents chilling units accumulated (CU) while *ForcingUnit* the forcing units accumulated (FU).

were calibrated against an observational dataset made up of field and experimental data, the latter obtained using grapevine cuttings exposed to a wide range of chilling durations to mimic the effect of short winters. The model calibrated on such a dataset should therefore be able to capture the variability expected in the future. The calibration parameters used for simulating grapevine phenology are given in Table 2.

2.4. Fruit-set index (FSI) and frost events estimation

The impact of frost was quantified by calculating the number of years with at least one day with minimum temperature lower than 0 °C ($T_{min} < 0$ °C) during the seven days interval around budbreak (frost events), and expressed as percentage over the 300 years of simulation. The frost events are associated to extreme weather for their severe and unexpected occurrence at a specific phenological stage (budbreak) that leads to considerable bud injuries. FSI estimates fruit-set as a function of air temperature during flowering. This index was obtained from greenhouse experiments described in the literature in which several grapevine varieties with different phenological cycles were exposed to varying diurnal temperatures around flowering time to evaluate their effect on fruit-set (Ewart and Kliewer, 1977; Haeseler and Fleming, 1967; Tukey, 1958; Table 3).

The outputs of the previous experiments (number of berries per cluster or fruit-set percentage) were used for describing the FSI curve (Table 3). In this context, the temperature of 25 °C was considered as optimum value for fruit-set and berry growth (Hale and Buttrose, 1974; Kozma, 2003; May, 2004; Vasconcelos et al., 2009; Winkler et al., 1974). Accordingly, the results obtained at different temperature treatments were standardized in relation to this optimal condition (T = 25 °C).

Based on this criterion, the equation of the temperature factor as shown in the photosynthesis scheme after Farquhar and von Caemmerer, 1982 was adopted for describing FSI (Eq. (3)):

$$FSI = \left(\frac{T - T_0}{T_{Opt} - T_0}\right)^q \cdot \left(\frac{T'_0 - T}{T'_0 - T_{Opt}}\right) \tag{3}$$

where T is the average maximum temperature of seven days around flowering, and T'_0, T_{Opt} and T_0 are the maximum, optimum and minimum temperature for growth, respectively, whilst q is a curve shape parameter. After calibration, the T'_0, T_{Opt} T_0 and q were 41 °C, 25 °C, 1 °C and 1.9, respectively. These parameters refer to the maximum, optimum and minimum threshold of daily average maximum temperature in seven days around flowering. The FSI ranges from 0 to 1, where 1 corresponds to the fruit-set obtained at the optimal temperature of 25 °C while values lower than 1 show a decrease of FSI for higher and lower temperature conditions.

3. Results

3.1. Present period dynamics

The earliest occurrences of budbreak and flowering stages are in south-western Europe (Figs. 1–4 and Supplementary Material Fig. A.1, A.2, A.3 and A.4). In general, budbreak is expected to occur after the 1st of March (Day Of Year, DOY 60), flowering after the 15th of May (DOY 135).

In Spain, for example, the budbreak date for all varieties ranges on average from DOY 95–113 and from DOY 109–124 in Italy, whilst budbreak is predicted later in northern regions, e.g. around DOY 125–142 in Germany. There is also a west-east oriented variation, i.e. from the Atlantic coast to the continental interior. In the United Kingdom, for instance, budbreak date ranges on average from DOY 109 and 133 considering all varieties (minimum values for Glera and maximum for Cabernet Sauvignon), which is much earlier than in Poland (DOY 136–151). A similar response was shown by flowering, which tends to occur earlier in Mediterranean regions (i.e. DOY 157–163 on average in Spain; DOY 160–166 on average in Italy) than central and northern regions (i.e. DOY 181–190 on average in Germany). More specifically, the four varieties showed differences in phenology dynamics between VE, E, ME and L phenological cycles. For budbreak, Glera showed the earliest occurrence in Europe (DOY 87–150) and Cabernet Sauvignon the latest (DOY 100–165). Instead, lower differences were found for flowering stage between early and late varieties (Glera: DOY 144–208; Cabernet Sauvignon: DOY 146–212).

The geographical phenology variability is associated to a corresponding impact of extreme events. A higher frequency of frost events during budbreak was estimated for western Europe where budbreak occurs earlier, most notably in Spain, France and the UK (i.e. in Spain: from 9 to 30%; France: from 3 to 41%; UK: from 3 to 50%). Conversely, Germany and Italy showed fewer frost events, which varied from 0% to 16% and from 1% to 11%, respectively (Figs. 5 and 6). On the other hand, FSI showed a geographical variability that ranges, on average, from 0.74 to 1 for all varieties with greater differences from northern to southern Europe (Fig. 7). Earlier flowering affected FSI results (Supplementary Material Fig. A.5, A.6, A.7 and A.8). Lower FSI values were obtained in northern than in southern regions. Spain, for instance, showed higher FSI than the UK (0.97 vs 0.81). The variability in phenological cycles of the four varieties showed higher risk of frost events for VE compared to L varieties. For instance, the earlier budbreak of Glera led to a higher frequency of frost events in France (42% on average) compared to Cabernet Sauvignon (3% on average). The VE and E varieties showed the highest frequency of frost events in western Europe, L was the least affected while ME was intermediate (Figs. 1 and 3 and Supplementary Material Fig. A.1 and A.3). Finally, the effect of extreme temperatures on FSI (e.g. higher and lower than the optimal range for flowering) was the same for all varieties (Figs. 2 and 4 and

Table 2
UniChill model calibration for different varieties.
Source: Fila (2012)

Varieties	a_c	b_c	c_c	b_f	c_f	C_{crit}	F_g	F_f
Glera	1.441	−14.719	−2.369	−0.191	18.216	20.776	12.122	33.209
Chardonnay	1.525	−5.317	3.531	−0.200	16.090	13.752	16.603	39.261
Merlot	0.927	7.400	7.464	−0.189	19.155	12.224	12.853	30.605
Cabernet S.	6.790	17.241	6.962	−0.194	17.187	6.853	19.734	40.341

a_c,b_c,c_c,b_f,c_f parameters for the curve shape; C_{crit} is the chilling requirement threshold (CU); F_g is the forcing requirement threshold for budbreak stage (FU) while F_f is the forcing requirement threshold for flowering stage (FU).

Table 3
Control temperature experiments used for describing the fruit-set index curve.

Varieties	Diurnal temperature treatment	Outputs	References
Cabernet Sauvignon	25/32.5/35/37.5/40 °C	Number of berries per cluster	Kliewer (1977)
Tokay	25/32.5/35/37.5/40 °C	Number of berries per cluster	Kliewer (1977)
Pinot noir	25/35/40 °C	% of fruit-set	Kliewer (1977)
Carignane	25/35/40 °C	% of fruit-set	Kliewer (1977)
Sylvaner	[a]25/15 °C	% of fruit-set	Ewart and Kliewer (1977)
Cabernet Sauvignon	[a]25/15 °C	% of fruit-set	Ewart and Kliewer (1977)
Zinfandel	[a]25/15 °C	% of fruit-set	Ewart and Kliewer (1977)
Concord (*Vitis labrusca*)	[b]65 °F/69 °F/79 °F/89 °F	Number of berries per cluster	Tukey (1958)
Concord (*Vitis labrusca*)	[c]60–65 °F/75–80 °F/90–95 °F	% of fruit-set	Haeseler and Fleming (1967)

[a] Only the grapevine that received no nitrogen treatment was considered.
[b] the experiment of 1956 was considered.
[c] the average of the interval of temperature treatment was considered.

Supplementary Material Fig. A.2 and A.4).

3.2. Future scenarios

All varieties showed earlier budbreak and flowering, which was more pronounced in central and eastern regions. In H2 estimates for Germany, budbreak shifts on average from a minimum of 28 to a maximum of 31 days earlier than the present period considering all varieties, whilst in Spain budbreak shifts by 7–11 days. Budbreak is earlier in all emission scenarios with H2 changing the most. In France, for example, the variation of budbreak time is on average from 8 to 11 days in L1 and from 16 to 22 days in H2 for all varieties.

Earlier flowering was also predicted across Europe (Figs. 2 and 4 and Supplementary Material A.2 and A.4). In France, the flowering stage advanced on average by 18–21 days for all varieties in the scenario with the highest variability (H2), while a slightly lower variation was predicted for Italy (on average from 16 to 18 days). Moreover, a higher variation of flowering stage is expected in Spain moving from L1 (from 2 to 5 days on average) to H2 (from 15 to 16 days on average) considering all varieties.

On this basis, a higher impact of climate change is estimated on budbreak for ME and L compared to VE and E varieties in western Europe. In France, for instance, Glera and Chardonnay showed the lowest variability between the present period and H2 (on average 16 days) while Merlot and Cabernet Sauvignon resulted as more affected by climate change (on average 21–22 days). Moreover, less difference in flowering time is expected between Chardonnay and Glera (on average 18–19 days) compared to Merlot and Cabernet Sauvignon (on average 21 days). In some regions such as Sardinia and Sicily, the model failed at calculating budbreak and flowering in H2 (e.g. stages not reached) because these stages were not completed within the time window allowed (white areas on the maps).

Depending on the predicted earlier budbreak, frost events were estimated to increase in central Europe. In Germany, frost events increase from L1 (0.3-28%) to H1 (4–39%), whilst they decrease for H2 (0.4–21%), considering Cabernet Sauvignon as the minimum value and Glera as the maximum (Fig. 6). By contrast, a marked reduction of frost risk is predicted for the Atlantic regions, notably France, Spain and the UK. In Spain for instance, frost events decrease for Glera from L1 (25%) to H2 (11%), respectively, whilst in the UK where frost events will range on average from 40% for L1 to 7% for H2 compared to the present period considering all varieties. In this context, the increasing temperature under the future scenarios determines a decrease in frost events percentage for Glera (i.e. from 42% in the present period to 18% for H2 on average) while a slight increase is expected for Cabernet Sauvignon in France (i.e. from 3% in the present period to 5% for H2 on average). However, the frequency of frost events remains higher for Glera compared to Cabernet Sauvignon across Europe.

Although the spatial variability of FSI followed a latitudinal and longitudinal gradient with different results between countries (e.g. UK vs Italy, Figs. 2 and 4), the use of varieties with different phenological cycles and different emission scenarios did not produce a strong variability on FSI (Figs. 2 and 4 and Supplementary Material Fig. A.2 and A.4). According to the lesser shift of flowering stage, the greater improvement of FSI was expected for northern Europe (e.g. UK) while a decrease of FSI was particularly evident in southern Europe (e.g. south of Italy).

4. Discussion

Over the last decades, the relationships between mean climate change and phenological timing have already been investigated using long-term datasets of several varieties (Tomasi et al., 2011). In this context, the combined effect of mean climate change and extremes is expected to become a fundamental crop yield-determining factor under future scenarios (Challinor et al., 2014; Yang et al., 2017), so an impact assessment must be performed considering both these issues (Moriondo and Bindi, 2007, 2006).

Accordingly, in this work we applied a statistical downscaling that, while removing the biases in RCM outputs, allowed for the reproduction of changes in climate variability as outlined by RCM simulations (Moriondo et al., 2010; Semenov and Stratonovitch, 2010).

The simulation results showed that in future scenarios budbreak and flowering advanced and this trend was more evident in the northeastern than southwestern regions of Europe. Similar results were obtained by Fraga et al. (2016), who evidenced an earlier occurrence for southern/western Spain as compared to northern/eastern European regions considering a standard variety suitable for several wine-producing regions. By contrast, the evaluation of the performance of varieties with different development timing (VE, ME, E, and L) in this paper emphasized that the effect of climate change and extreme events differs depending on the length of phenological cycles.

This study evidenced, especially for western Europe, that L grapevine varieties were earlier than VE and E while ME was intermediate. These results are in accordance with the simulations of Webb et al. (2007), which highlighted that warmer climate conditions had greater influence on the budbreak stage of L compared to E in five out of six locations investigated in Australia.

The warmer climate showed a relevant impact on phenology stages, especially on budbreak estimation. Unlike previous studies in which the prediction of budbreak date is exclusively based on thermal time models (e.g. Zapata et al., 2017), this study highlights that the effect of chilling temperatures during dormancy period affects the budbreak simulation. These results are supported by a stable calibration in which field and grapevine cuttings data were used to calibrate and validate the phenology model. By contrast, the use of only field phenology data such as shown in Webb et al. (2007) may not allow to capture a wider range of variability (i.e. cold and mild winter) that affects dormancy period to be explored. Indeed, as the endo-dormancy period depends on a narrow temperature interval according to the adopted model, it is possible that

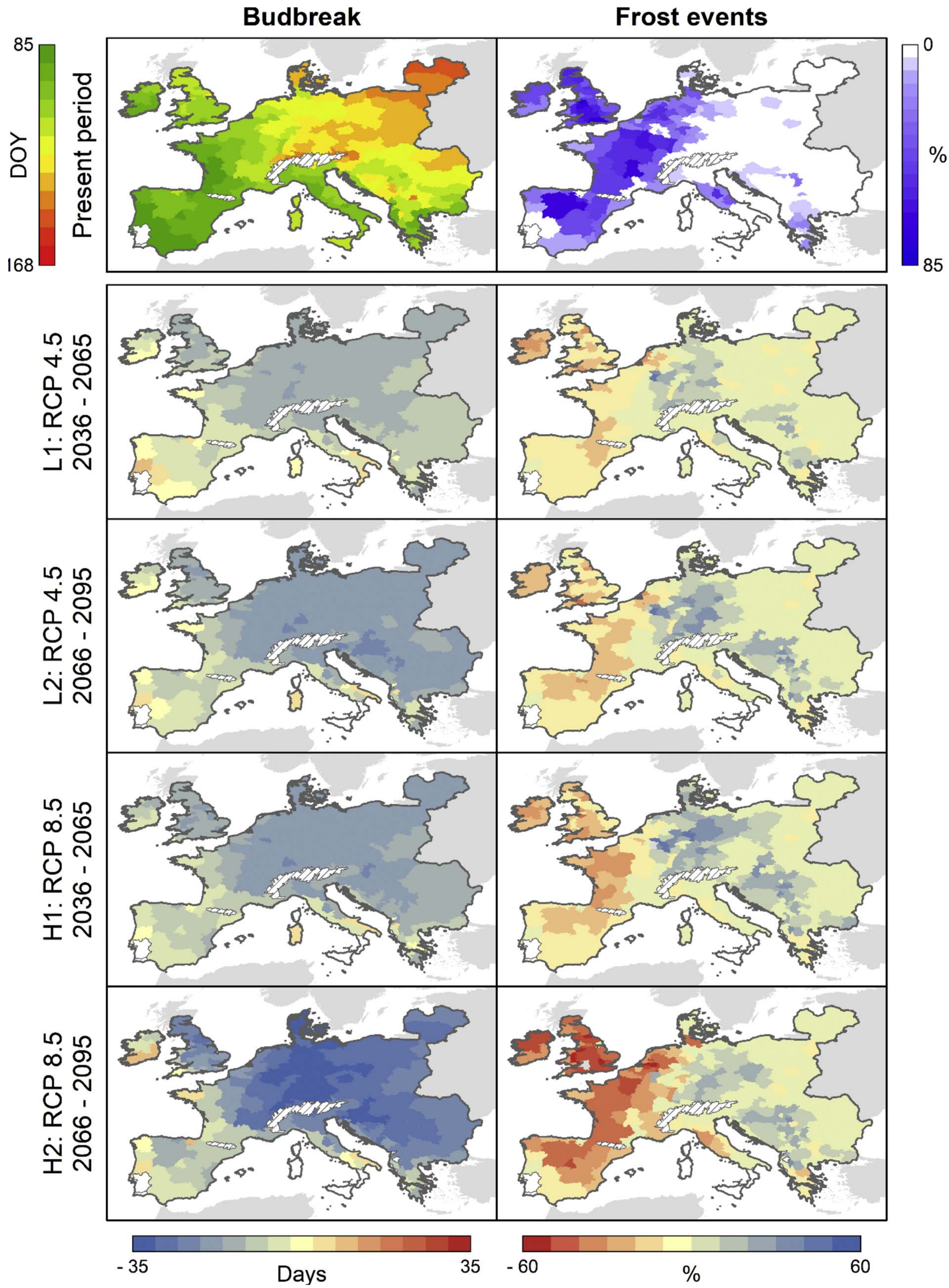

Fig. 1. Budbreak stage and frost events for Glera variety at European NUTS2 regional scale. The maps of future emission scenarios (L1, L2, H1, H2) are obtained comparing present with future data (Days = number of days in advance or delay compared to the present period). The white areas on the map correspond to the NUTS2 zones in which budbreak is not reached while the stippled areas refer to the grid points excluded by the simulation.

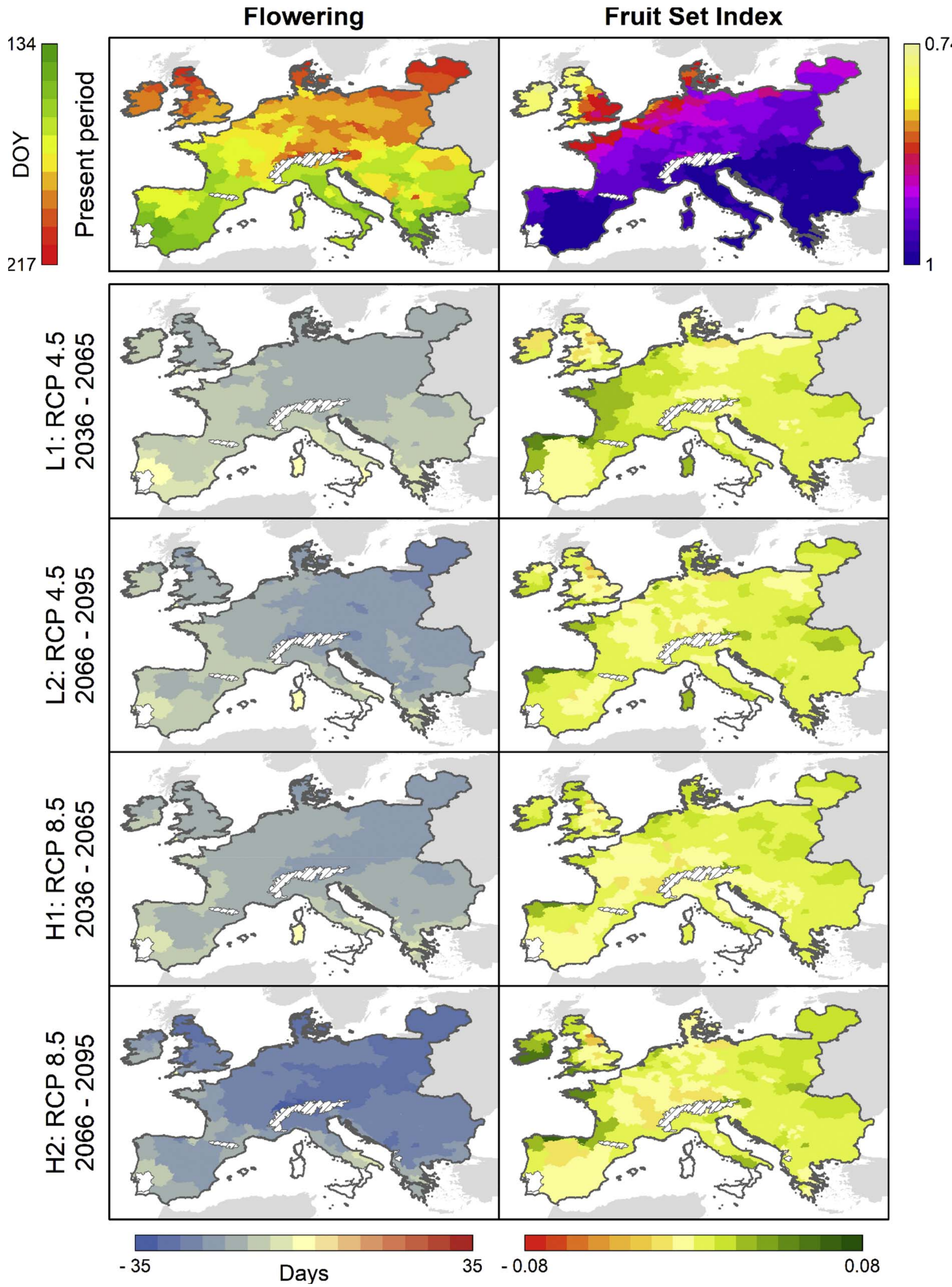

Fig. 2. Flowering stage and fruit-set index for Glera variety at European NUTS2 regional scale. The maps of future emission scenarios (L1, L2, H1, H2) are obtained comparing present with future data (Days = number of days in advance or delay compared to the present period). The white areas on the map correspond to the NUTS2 zones in which budbreak is not reached while the stippled areas refer to the grid points excluded by the simulation.

in some environments high winter temperatures do not completely meet chilling requirements (Nendel, 2010), leading to slow dormancy exit (i.e. Spain). This study showed that in the near future, some Mediterranean regions (i.e. Sardinia and Sicily in H2), may suffer from excessive temperatures that result in a lack of chilling units accumulation and finally in a missed budbreak. This was predicted for other

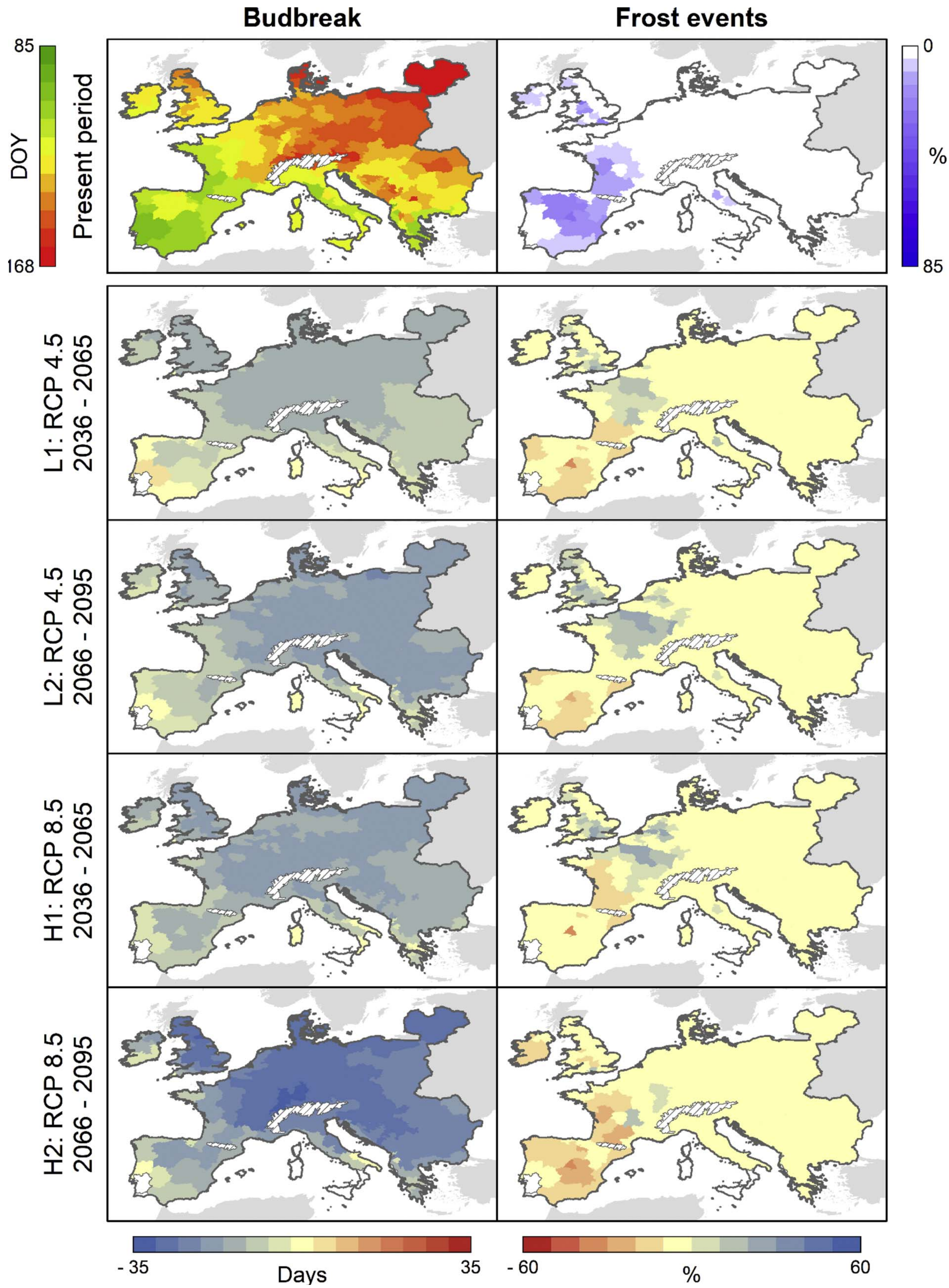

Fig. 3. Budbreak stage and frost events for Cabernet Sauvignon variety at European NUTS2 regional scale. The maps of future emission scenarios (L1, L2, H1, H2) are obtained comparing present with future data (Days = number of days in advance or delay compared to the present period). The white areas on the map correspond to the NUTS2 zones in which budbreak is not reached while the stippled areas refer to the grid points excluded by the simulation.

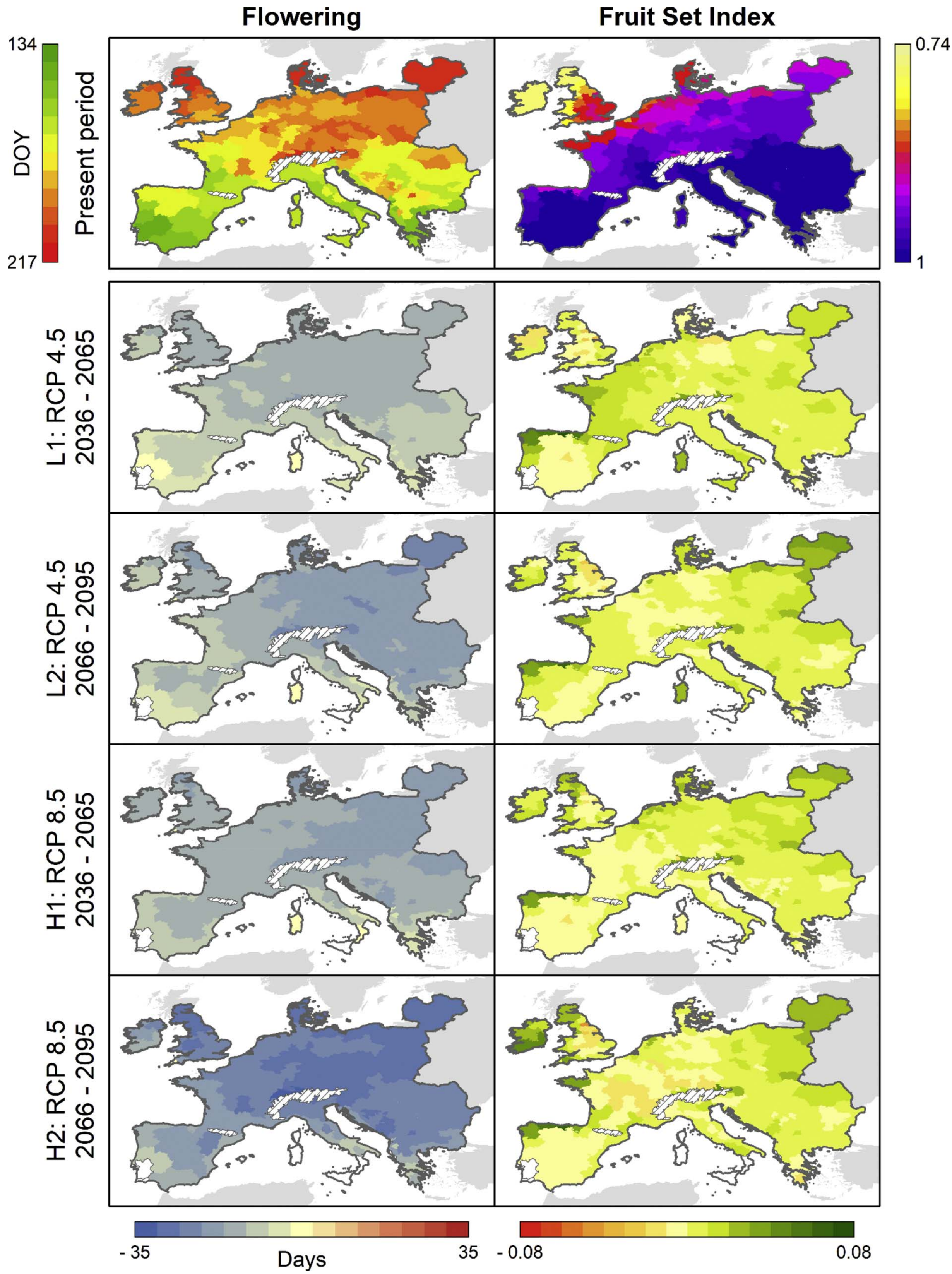

Fig. 4. Flowering stage and fruit-set index for Cabernet Sauvignon variety at European NUTS2 regional scale. The maps of future emission scenarios (L1, L2, H1, H2) are obtained comparing present with future data (Days = number of days in advance or delay compared to the present period). The white areas on the map correspond to the NUTS2 zones in which budbreak is not reached while the stippled areas refer to the grid points excluded by the simulation.

species like olive trees (Gabaldón-Leal et al., 2017) in which the lack of chilling units in southern Andalusia (Spain) suggests as these areas will be less suitable for olive growth in the near future. These results are supported by this study in which the increased temperatures in southern regions (i.e. Spain) are expected to lead to a strong delay of chilling accumulation during the first part of the dormancy period in

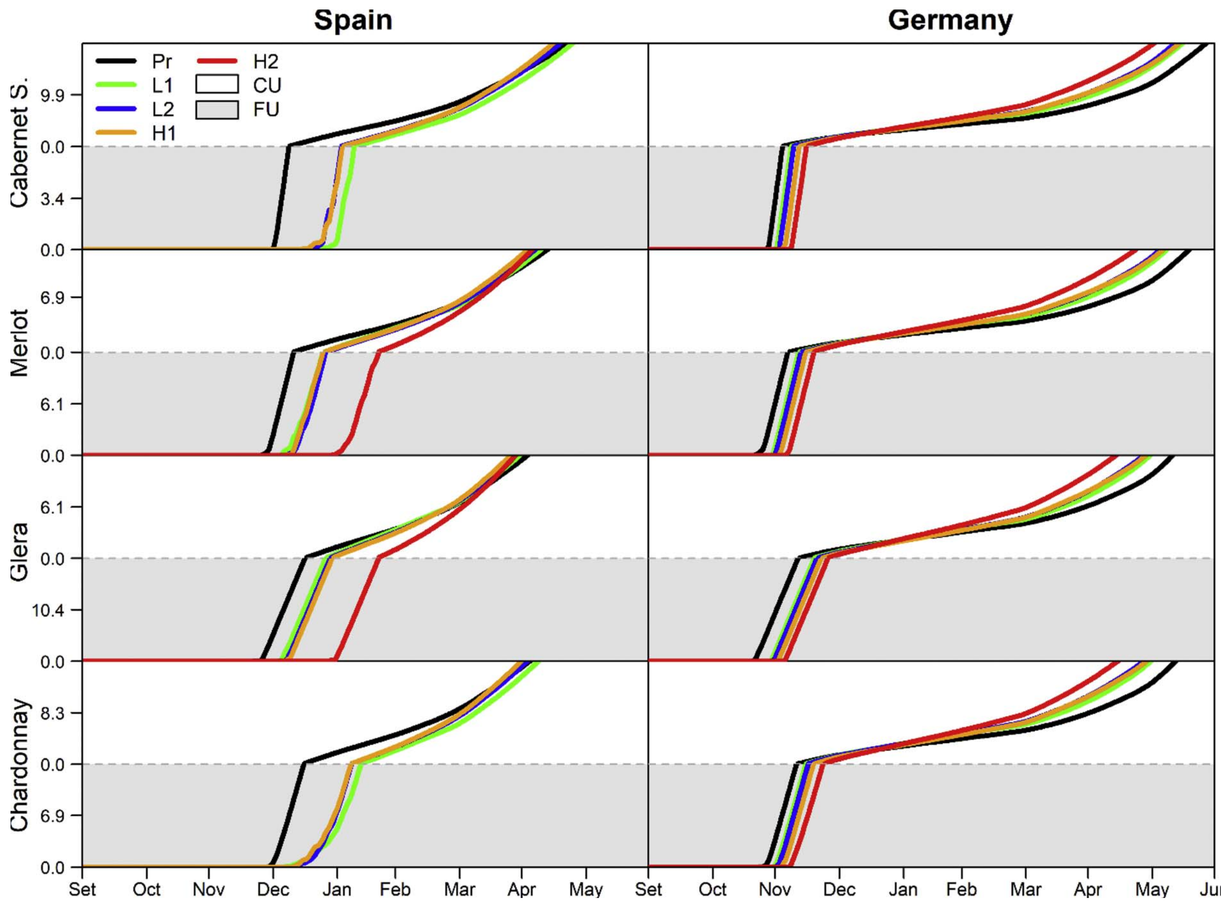

Fig. 5. Trend of endo-dormancy and eco-dormancy period under different climatic scenarios considering an average year calculated using the mean of each day of 300 years of simulation on two representative grid points of Spain and Germany (Pr = Present; L1 = Low emission Scenario RCP 4.5 2036–2065; L2 = Low emission Scenario RCP 4.5 2066–2095; H1 = High emission Scenario RCP 8.5 2036–2065; H2 = High emission Scenario RCP 8.5 2066–2095; CU = Chilling Units; FU = Forcing Units).

future scenarios (Fig. 5). On the other hand, the higher temperatures in late winter influence the eco-dormancy period by reducing the forcing accumulation time. As an example (Fig. 5), the chilling requirement in Germany is expected to be already satisfied in early winter while a longer eco-dormancy period is shown until budbreak date. In this case, the impact of increasing temperatures is greater for the European regions characterized by a longer dormancy cycle.

The effect of increased temperature on budbreak is not the only issue that influences grapevine phenology. In general, an earlier budbreak results in an earlier following stage (flowering) even if with generally less pronounced effects, as also observed by Fraga et al. (2016). This is especially due to the shift of budbreak that projects the following stage into a relatively cooler climate window that slows the thermal unit accumulation finally leading to a less evident advancement of flowering stage (Sadras and Moran, 2013). The shift of budbreak and flowering also determines an earlier physiological maturity in hotter and drier months (Dry, 1988).

Importantly, the results obtained in this study highlighted that for grapevine, as for other species like maize, wheat and olive tree (Barlow et al., 2015; Chung et al., 2014; Gabaldón-Leal et al., 2017), changes in the occurrence of phenology stages may expose grapevine to a higher frequency of extreme events and this effect is strictly dependent on the varietal phenological cycle.

In particular, we focused on budbreak and flowering stages variability that is known to have detrimental effects on final grape yield and quality (i.e. yield reduction: Molitor et al., 2014; Trought et al., 1999 production of unbalanced wine: Jones et al., 2005). The sensitivity of grapevine tissues to frost events and the consequent bud injury has a strong impact on grape growth and yield. According to Mullins et al. (1992) and Trought et al. (1999), the occurrence of early frost events determines the depletion of reserves needed for shoot growth, leading to a decrease in shoot development and lower fruit yield with several economic repercussions. This study evidenced that a warmer climate resulted in a general decrease of frost events frequency especially in Mediterranean regions and on the northern fringes of Europe, while in eastern regions these events are even expected to increase (i.e. Germany until H1; Fig. 6). Different varieties provided insights into variations of risk exposure among those examined. A reduced frost events frequency is more evident for VE and E varieties where the frost events frequency decreases at a higher rate with respect to ME and L varieties in western European regions. Similarly, Molitor et al. (2014) showed that frost events are expected to decrease for the early variety Muller Thurgau, as the earlier budbreak does not outweigh the seasonal temperature pattern.

By contrast, in Eastern Europe, frost events frequency is predicted to increase with respect to the baseline, especially for VE and E, while ME and L are less affected. These results therefore suggest the adoption of frost resistant and/or ME and L varieties, especially in those regions where frost events are predicted to increase. Indeed, although the climate conditions in some cooler areas are currently more favorable to VE and E varieties with a short growing season, the warmer conditions of future scenarios may lead to more suitable conditions for ME and L.

The impact of stressful temperatures during flowering is a key factor for final yield (Hale and Buttrose, 1974; Vasconcelos et al., 2009). Indeed, given that optimal temperatures for flowering range from 20 to 30 °C (Kozma, 2003; May, 2004), higher and lower temperatures during this stage impact negatively on flower formation, fruit-set, pollen germination and ultimately on grape production (Ewart and Kliewer,

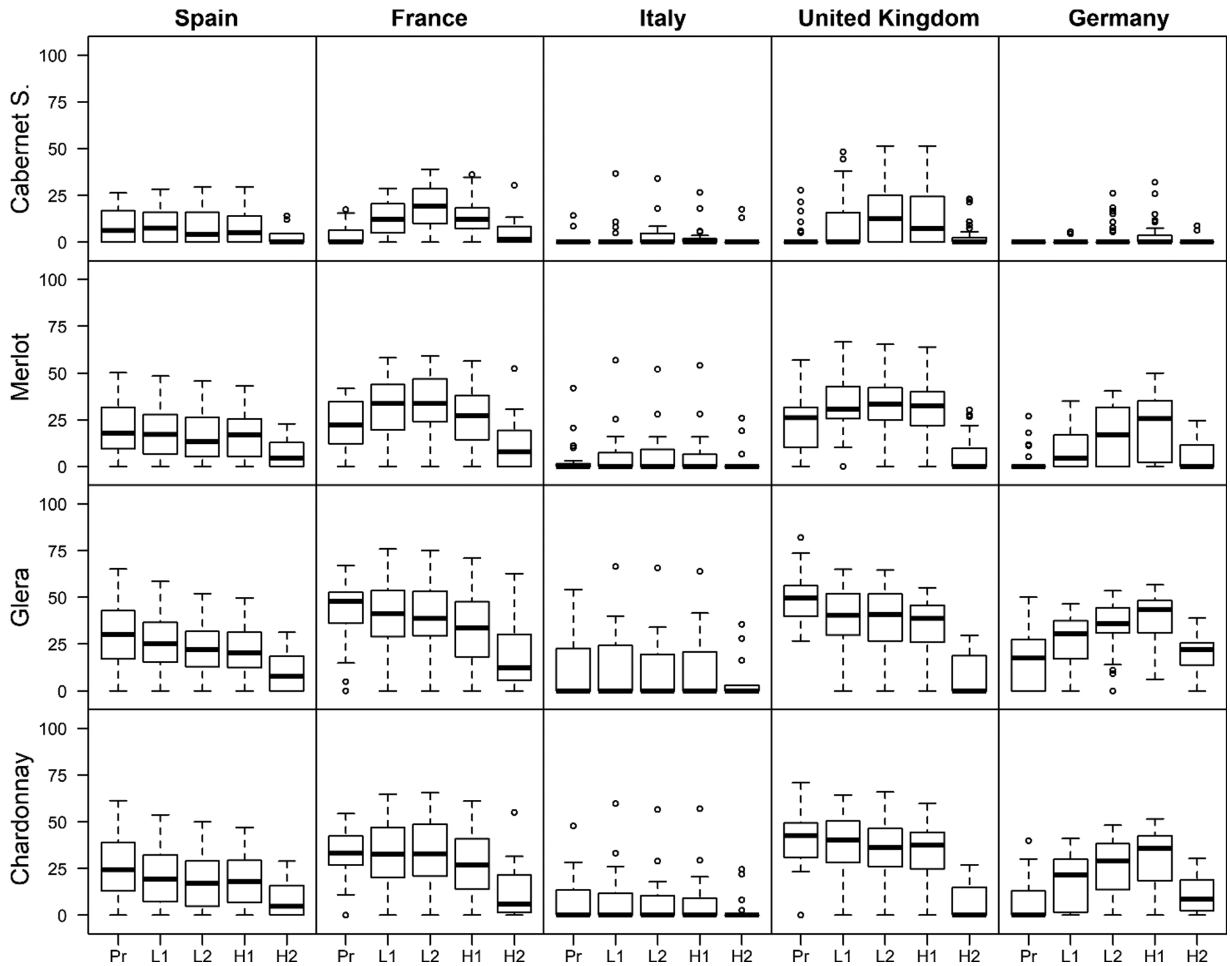

Fig. 6. Distribution of frost events for present and future scenarios for each variety and country (Pr = Present; L1 = Low emission Scenario RCP 4.5 2036–2065; L2 = Low emission Scenario RCP 4.5 2066–2095; H1 = High emission Scenario RCP 8.5 2036–2065; H2 = High emission Scenario RCP 8.5 2066–2095).

1977). According to Ebadi et al. (1995), for example, a 30% decrease in flower size and pollen germination was found for Chardonnay and Shiraz with temperature drops before flowering.

In this study, the temperature around flowering date plays a key role in the FSI performances (Supplementary Material Fig. A.5, A.6, A.7 and A.8). Although the variability of FSI between countries is evident, very low differences have been found between variety and scenarios (Fig. 7). While the optimal FSI reported for southern regions (i.e. Italy) is related to the positive temperature conditions around flowering, the lower temperatures in northern areas (i.e. UK) show a negative effect on FSI performances. Moreover, flowering date estimations do not differ excessively between VE, E, ME and L varieties under future scenarios. The limited shift of the flowering stage between varieties led to complete the forcing requirement for flowering in a similar period. As mentioned before, this regulation process is due to the earlier budbreak in cooler time windows that slows the rate of forcing units accumulation for flowering (e.g. grapevine: Sadras and Moran, 2013; wheat: Sadras and Monzon, 2006).

Based on the results of this study, the effects of climate change and extreme events on early season phenology of grapevines are most evident on budbreak. Indeed, greater differences between VE, E, ME and L have been shown for frost events compared to FSI. More specifically, our results suggest that the effect of frost events at budbreak stage represents the most important factor for the selection of varieties.

5. Conclusions

This study highlighted the estimated dynamics of grapevine phenology (budbreak and flowering) in Europe at present and in the future considering the impact of mean climate change and the occurrence of extreme events at specific stages. Our results showed a general earlier occurrence of the phenology stages under future scenarios, which follows a latitudinal and longitudinal geographical gradient (e.g. over the H2 emission scenario budbreak occurs 28–31 days earlier in Germany and 7–11 days in Spain while flowering occurs 18–21 days earlier in France and 16–18 days in Italy). The interest in studying the impact of climate change on the phenology dynamics, as performed in this work, lies in understanding the frequency of the extreme events for four widespread varieties in Europe. In this context, the great impact of frost events at budbreak, more than suboptimal temperatures at flowering, resulted a key factor for the selection of grapevine varieties in Europe.

The phenological outcomes have been obtained taking into account the effect of temperature only and applied on the entire European domain. Accordingly, future researches should consider the effect of more weather variables (e.g. rainfall, daylength, etc.) excluding the marginal areas in which grapevine is not usually grown (e.g. unsuitable soil and climate). Future works can also take advantage of the combined impact assessment of climate change and extreme events, to be applied on grape biomass accumulation and quality process associated to different grapevine phenological cycles. An even more integrated assessment would likely be more informative about the overall effects derived from grapevine growing season shifts and on fruit/wine production in the future, ultimately allowing for greater understanding of appropriate adaptation strategies.

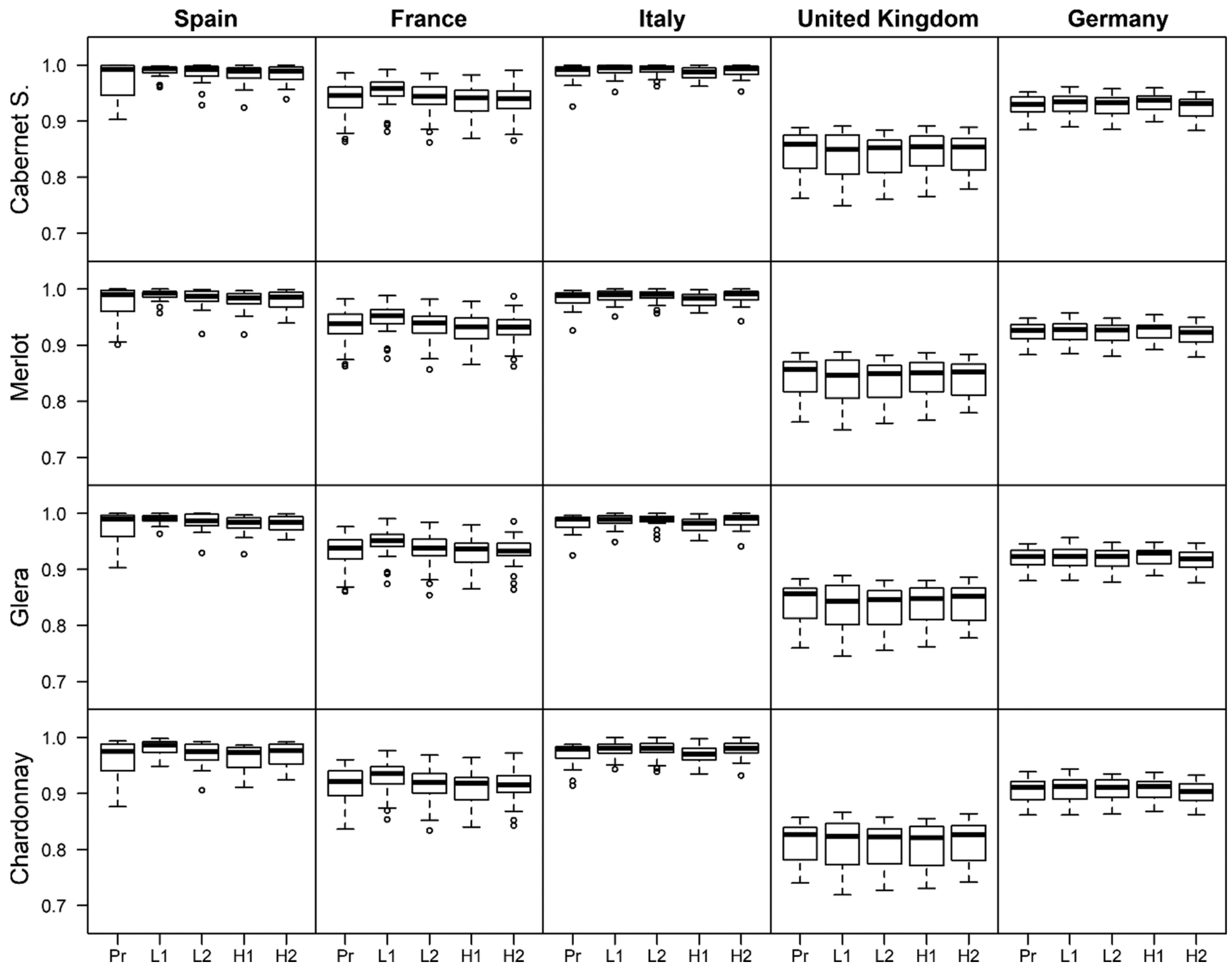

Fig. 7. Distribution of the fruit-set index for present and future scenarios for each variety and country (Pr = Present; L1 = Low emission Scenario RCP 4.5 2036–2065; L2 = Low emission Scenario RCP 4.5 2066–2095; H1 = High emission Scenario RCP 8.5 2036–2065; H2 = High emission Scenario RCP 8.5 2066–2095).

Acknowledgements

R. Ferrise and M. Bindi acknowledge the JPI FACCE MACSUR2 project.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2017.11.018.

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